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### Citation for published version:

Stratford, TJ & Bisby, LA 2010, Temperature Effects in Adhesively Bonded FRP Strengthening Applied to Steel Beams: Experimental Observations. in LP Ye, P Feng & QR Yue (eds), *Advances in FRP Composites in Civil Engineering: Proceedings of the 5th International Conference on FRP Composites in Civil Engineering (CICE 2010)*, Sep 27–29, 2010, Beijing, China. Springer-Verlag GmbH, BERLIN, pp. 886-889, 5th International Conference on FRP Composites in Civil Engineering, Beijing, 27/09/10.  
[https://doi.org/10.1007/978-3-642-17487-2\\_195](https://doi.org/10.1007/978-3-642-17487-2_195)

### Digital Object Identifier (DOI):

[10.1007/978-3-642-17487-2\\_195](https://doi.org/10.1007/978-3-642-17487-2_195)

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Peer reviewed version

### Published In:

Advances in FRP Composites in Civil Engineering

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# Temperature Effects in Adhesively Bonded FRP Strengthening Applied to Steel Beams: Experimental Observations

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**ABSTRACT:** FRP plates can be used to strengthen a steel beam in flexure, but this method relies critically upon the adhesive used to bond the FRP plate to the existing steel member. When the temperature of the strengthened beam is increased, differential thermal expansion occurs between the steel and FRP. In addition, the glass transition temperature of a typical two-part ambient-cure epoxy adhesive is typically between about 50°C and 65°C, and the stiffness and strength of the adhesive will decrease at temperatures somewhat below the glass transition temperature. This paper reports tests conducted on steel beams strengthened with CFRP plates and ambient-cure epoxy adhesive. Load was applied to the beams in four-point bending, and the temperature of the strengthening was then increased until failure occurred. Slip deformations were directly observed across the adhesive joint, giving an indication of the performance of the strengthening at elevated temperatures. The consequences of this preliminary study upon the design of externally-bonded FRP strengthening for steel structures are discussed.

## 1 INTRODUCTION

Properly designed and installed FRP strengthening often requires less installation equipment and time than other strengthening techniques (such as bonded steel plates or bolted strengthening solutions). Consequently, FRP strengthening is an increasingly popular method to extend the life of steel and cast iron structures (CIRIA 2004).

To enable easy installation, two-part ambient-cure epoxy resins are commonly used to bond the FRP to the existing structure without the need for elevated temperature curing. These ambient-cure epoxies soften at low glass-transition temperatures of typically 50-65°C (Concrete Society 2004), which are similar to the temperatures considered during the design of steel bridges in the UK (Highways Agency 2001).

Research into the elevated temperature performance of bonded FRP strengthening has concentrated upon the *high* temperatures present during a fire (e.g.: Kodur, Bisby & Green 2007); this paper investigates *warm* temperatures (< 100°C). It presents results from a preliminary experimental study conducted on CFRP strengthened steel beams, the aims of which were to:

- Establish how an FRP plate bonded beam is affected by warm temperatures.

- Study slip deformation across the adhesive joint under warm conditions.

### 1.1 Thermal effects in bonded strengthening

Two thermal effects act when a plated beam is heated:

- differential expansion between the CFRP plate and the metal; and
- glass transition of the adhesive, which reduces the strength and of stiffness of the adhesive.

Differential thermal expansion causes high shear stresses across the adhesive joint. Elastic bond stress analysis predicts that for a typical bridge strengthening scheme, the thermal shear and peel stresses can be greater than those due to traffic loading (Denton 2001, Stratford and Cadei 2005).

However, the implications of differential thermal expansion and the glass transition of the adhesive are not obvious. The reduction in adhesive strength at elevated temperatures is accompanied by a reduction in the adhesive stiffness and an increase in deformation capacity, both of which could be beneficial to the overall strength of the adhesive connection.

## 1.2 Epoxy adhesive at elevated temperatures

Figure 1 shows the glass transition for the epoxy bonding adhesive used in the present tests. This is a 2-part, ambient-cure adhesive, sold specifically for plate bonding applications. The reduction in stiffness with temperature shown in the figure was obtained by dynamic mechanical analysis (DMA) of five adhesive samples. The specimens (15×10×1mm) were tested in a double cantilever configuration, hence Figure 1 plots normalised flexural stiffness; however, this is also the variation in adhesive shear stiffness with temperature. The tests were conducted after 15 days ambient cure (whereas the manufacturer specifies full cure after 5 days at 25°C).

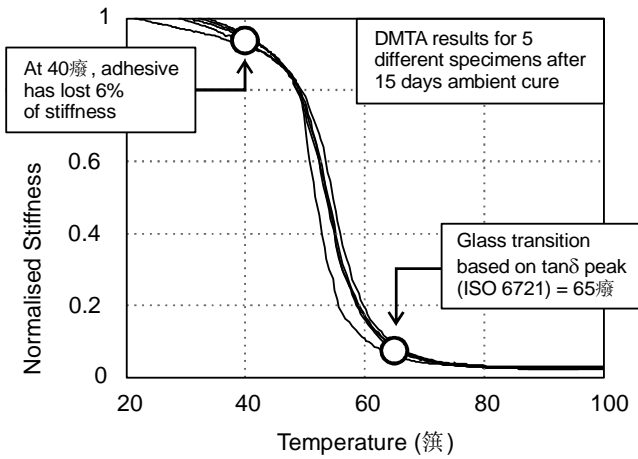


Figure 1. Measured loss in stiffness of the epoxy bonding adhesive through the glass transition.

At 40 °C, the adhesive stiffness has reduced to 94% of its ambient value, a change that would normally be considered significant for structural design. The glass transition, however, is not normally characterised in full, but by single temperature,  $T_g$ . The definition of  $T_g$  varies depending upon the phenomenon being tested (Ludwig *et al.* 2008). ISO 6721 (2002) defines the glass transition temperature for DMA as the peak in the  $\tan\delta$  curve, which is the ratio of the loss modulus to the storage modulus (simplistically, the ratio of plastic deformation to elastic deformation). This gives  $T_g = 65^\circ\text{C}$ , for which the adhesive stiffness has reduced to less than 10% of its ambient value.

## 2 EXPERIMENTAL ARRANGEMENT

Six steel I-beams were strengthened using pultruded CFRP plates and the ambient cure epoxy adhesive characterised in Figure 1. The beams were loaded in inverted 4-point bending, as shown in Figure 2. The cross-sectional dimensions and material properties are shown in Figure 3.

The end of the strengthening plate was heated from above using a silicone rubber electrical heating pad, the temperature of which was controlled according to a thermocouple on the surface of the plate. The temperature of the flange of the steel beam was measured using two further thermocouples located at the end of the plate ( $T_2$ ) and 160mm from the end of the plate ( $T_1$ ). These temperatures are assumed to be representative of the temperature of the adhesive, due to the high thermal conductivity of the steel.

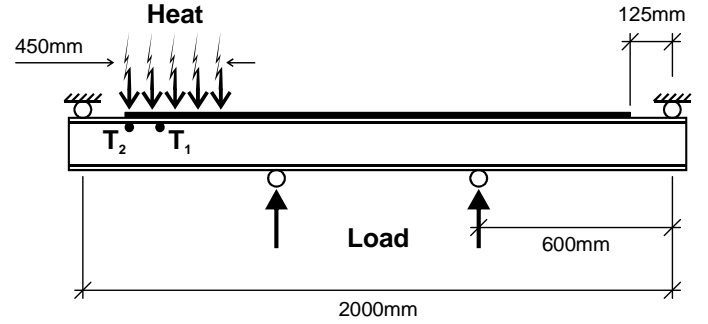


Figure 2. The test arrangement.

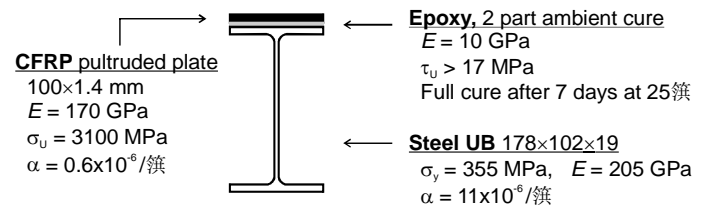


Figure 3. Cross-section dimensions and material properties of the strengthened beams. (The material properties for the adhesive and CFRP plate are from the manufacturer's data sheet).

Table 1 summarises the tests conducted. The capacities of the strengthened beam (1) and unstrengthened beam (7) were found at ambient temperature. Test 6 failed prematurely due to air voids in the bondline, so does not represent the true strengthened capacity of the beam.

Beams 2 to 5 were loaded to above their unstrengthened capacity. This load was held constant whilst the temperature in the adhesive was increased until failure occurred, as shown schematically in Figure 4. Each of the two ends of beams 4 and 5 were tested separately (tests 4a, 4b; 5a, 5b).

Table 1. Details of experimental program and headline results.

ID	Load (kN)	Temperature $T_2$ (°C)	Comment
1	<b>190.0</b>	Ambient	Capacity of a strengthened beam (l.t. buckling)
6	<b>(155.6)</b>	Ambient	Premature failure due to poor bonding
7	<b>140.4</b>	Ambient	Capacity of an unstrengthened beam (l.t. buckling)

2	150	<b>65</b>	Plate debonding failure
3	160	not available	Data acquisition error
4a	170	<b>74</b>	Plate debonding failure.
4b	170	<b>74</b>	Plate debonding failure.
5a	180	<b>60</b>	Plate debonding failure.
5b	180	<b>64</b>	Plate debonding failure.

### 2.1 Image analysis of the adhesive joint

High resolution digital images were recorded at 10 second intervals during the tests, for later analysis to establish the deformation across the adhesive joint. The images focused upon the heated end the plate, where the side of the CFRP, adhesive and beam flange had first been painted with a high-contrast texture, as shown in Figure 5.

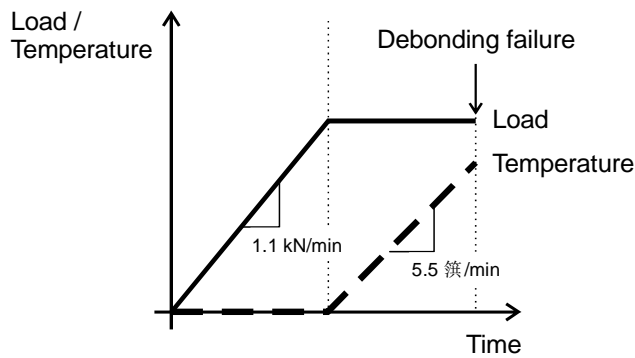


Figure 4. Schematic loading and heating history.

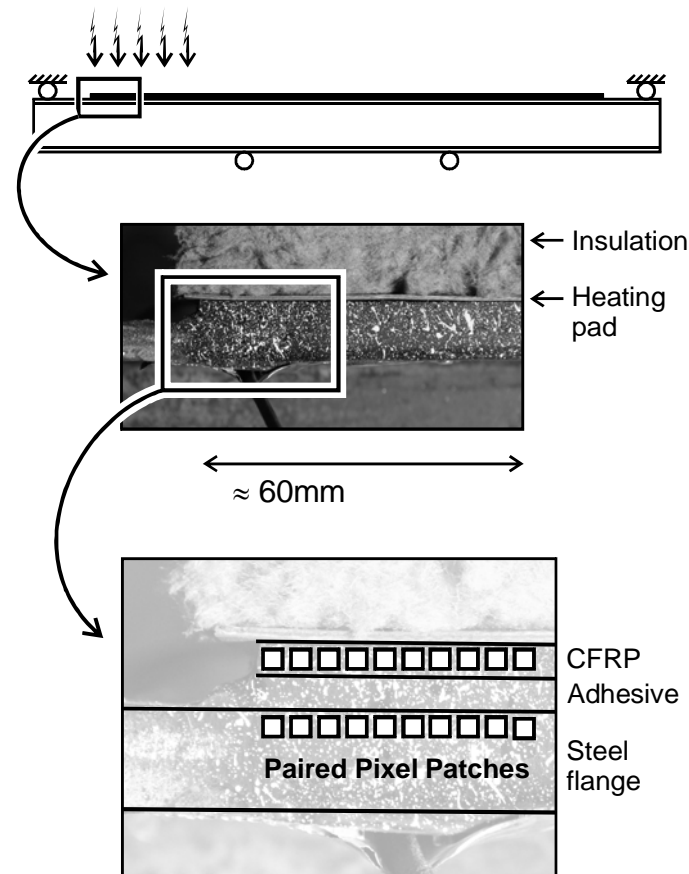


Figure 5. Measurement of slip displacement across the adhesive joint by digital image analysis.

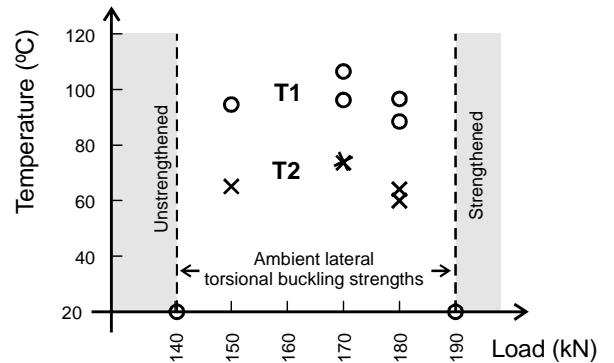
The images were analysed using a bespoke image-processing algorithm (White *et al.* 2003) that tracks the movement of patches of pixels. The relative horizontal displacement of pairs of patches in the CFRP plate and flange of the beam allowed the slip (shear displacement) across the adhesive joint to be determined (Figure 5).

## 3 RESULTS

Table 1 summarises the key results from the tests. The strengthening failed adhesively at the adhesive-steel interface in every case, resulting in debonding of the plate from the beam along the 450mm heated length. Failure of the adhesive joint was followed by lateral-torsional buckling of the steel beam, as for the unstrengthened beam at ambient temperature.

Figure 6 plots the failure temperature and applied load for the tests, showing the temperature at both thermocouples. There is no discernible trend between the failure temperature and applied load. All tests failed after 25 to 30 minutes of heating.

The temperature at the plate end ( $T_2$ ) is lower than the temperature within the plate ( $T_1$ ) due to conduction into the unheated steel beam towards the supports (Figure 2). Debonding failure usually initiates at the stress concentration at the end of the plate, thus  $T_2$  is more representative of the failure tempera-



ture.

Figure 6. Reduction in beam strength due to temperature

### 3.1 Slip displacements across the adhesive joint

The plate-end slip displacements obtained using image analysis are plotted in Figure 7 for all tests. Significant slip deformation occurred from 40°C, and

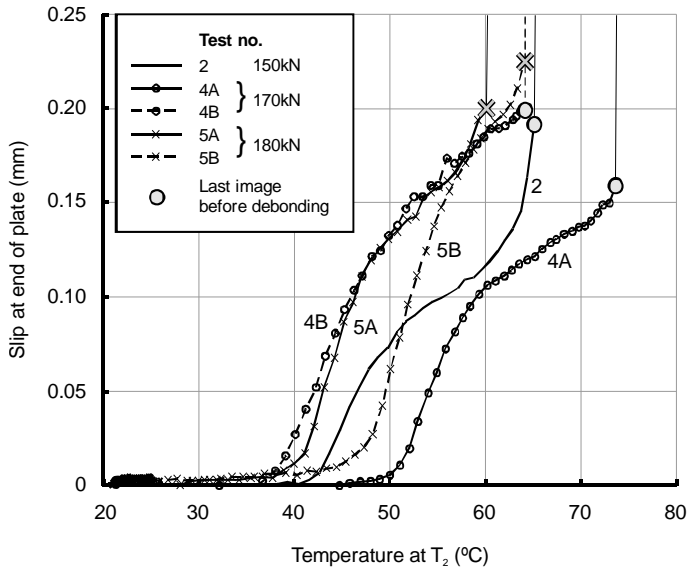


Figure 7. Plate end slip variation with temperature for all tests. this slip increased to failure. The slips recorded by the last image before failure were in the range 0.16 to 0.23mm; the actual failure slip will have been slightly higher as the last image was taken up to 10 seconds before debonding occurred.

An example of the complete output from the image analysis is shown in Figure 8 for Test 5B. This plots the slip displacement with position from the plate end and against temperature. Slip occurs along the whole of the observed length of the adhesive joint, with little variation in slip along the beam.

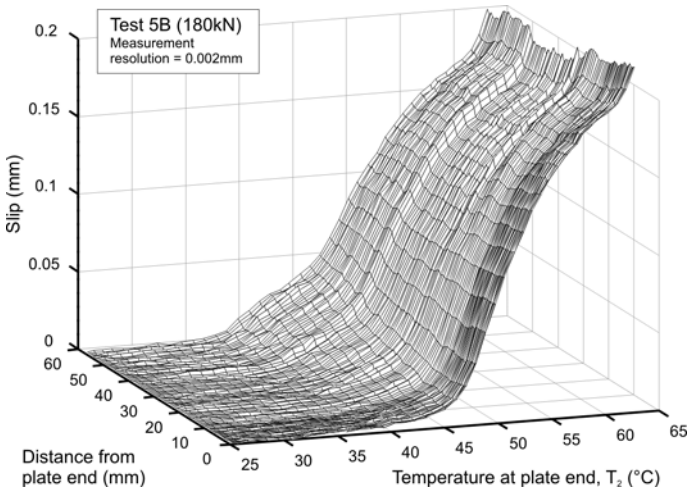


Figure 8. Slip distribution variation for Test 5B.

## 4 DISCUSSION

Significant adhesive joint slip occurred from around 40°C, well before the plate debonded from the steel beam (Figures 7 & 8). This slip behaviour follows the glass transition response of the adhesive shown in Figure 1. Debonding occurred at a plate end temperature of around 65°C, the ISO 6721 glass transition temperature; however, it should be noted that Test 5a failed at 60°C (Table 1).

The significance of the slips observed prior to failure is not obvious. A linear-elastic analysis of bond stress (Stratford & Cadei 2005) using the ambient material properties supplied by the manufacturer (Figure 3) predicts that the shear strength of the adhesive is reached at a slip displacement  $\approx 0.005\text{mm}$ , and that this slip is localised at the end of the plate. This elastic slip is only slightly greater than the measurement resolution of the image analysis method and so is not visible in Figure 8.

The glass transition that occurs when the strengthened beam is heated results in a weaker adhesive; however, the adhesive is also less stiff and has a greater deformation capacity. Thus, load is transferred between the strengthening plate and the flange of the beam over a longer bond length than at ambient temperature.

Close examination of Figure 8 reveals that the slip *increases* with distance from the end of the plate for  $T_2 \approx 45^\circ\text{C}$ . This is probably because the adhesive temperature increases away from the plate end (as noted above), and is further into the glass transition.

## 5 CONCLUSIONS

The test results presented in this paper demonstrate that the strength of an FRP-plated steel beam can be significantly reduced by warm temperatures ( $\approx 65^\circ\text{C}$ ). Significant irrecoverable slip deformation occurs across the adhesive joint prior to failure (from  $\approx 40^\circ\text{C}$ ) due to the glass transition of the adhesive.

It is not straightforward to predict the consequences of the adhesive glass transition upon the strengthened beam. The increased deformation capacity and reduced stiffness of the adhesive at elevated temperatures allow stress redistribution along the length of the strengthening. Consequently, greater load can be transferred between the plate and beam than is suggested by the reduction in strength of the adhesive through the glass transition.

## 6 ACKNOWLEDGEMENTS

The experiments were undertaken by Cameron Gillespie and Martin Moran for their MEng theses. The authors gratefully acknowledge the support of the School of Engineering at the University of Edinburgh, which is part of the Edinburgh Research Partnership in Engineering and Mathematics.

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